COMPRESSOR STALL AND SURGE CONTROL USING AIRFLOW ASYMMETRY MEASUREMENT

This application has been filed under 35 U.S.C. 371 based on PCT/US95/17145 filed on Nov. 2, 1995, which is a CIP of earlier application Ser. No. 08/355,763, now abandoned.

TECHNICAL FIELD

This invention relates to techniques for detecting and controlling dynamic compressor stall and surge, for instance in gas turbine engines.

BACKGROUND OF THE INVENTION

In a dynamic compressor operating under normal, stable flow conditions, the flow through the compressor is essentially uniform around the annulus, i.e. it is axisymmetric, and the annulus-averaged flow rate is steady. Generally, if the compressor is operated too close to the peak pressure rise on the compressor pressure rise versus mass flow, constant speed performance map, disturbances acting on the compressor may cause it to encounter a region on the performance map in which fluid dynamic instabilities, known as rotating stall and/or surge, develop. This region is bounded on the compressor performance map by the surge/stall line. The instabilities degrade the performance of the compressor and may lead to permanent damage, and are thus to be avoided.

Rotating stall can be viewed as a two-dimensional phenomena that results in a localized region of reduced or reversed flow through the compressor which rotates around the annulus of the flow path. The region is termed “stall cell” and typically extends axially through the compressor. Rotating stall results in reduced output (as measured in annulus-averaged pressure rise and mass flow) from the compressor. In addition, as the stall cell rotates around the annulus it loads and unloads the compressor blades and may induce fatigue failure. Surge is a one-dimensional phenomena defined by oscillations in the annulus-averaged flow through the compressor. Under severe surge conditions, reversal of the flow through the compressor may occur. Both types of instabilities should be avoided, particularly in aircraft applications.

In practical applications, the closer the operating point is to the peak pressure rise, the less the compression system can tolerate a given disturbance level without entering rotating stall and/or surge. Triggering rotating stall results in a sudden jump (within 1–3 rotor revolutions) from a state of high pressure rise, efficient, axisymmetric operation to a reduced pressure rise, inefficient, non-axisymmetric operation. Returning the compressor to axisymmetric operation (i.e., eliminating the rotating stall region) requires lowering the operating line on the compressor performance map to a point well below the point at which the stall occurred. In practical applications, the compressor may have to be shut down and restarted to eliminate (or recover from) the stall. This is referred to as stall hysteresis. Triggering surge results in a similar degradation of performance and operability.

As a result of the potential instabilities, compressors are typically operated with a “stall margin”. Stall margin is a measure of the ratio between peak pressure rise, i.e. pressure rise at stall, and the pressure ratio on the operating line of the compressor for the current flow rate. In theory, the greater the stall margin, the larger the disturbance that the compression system can tolerate before entering stall and/or surge.

Thus, the design objective is to incorporate enough stall margin to avoid operating in a condition in which an expected disturbance is likely to trigger stall and/or surge. In gas turbine engines used to i power aircraft, stall margins of fifteen to thirty percent are common. Since operating the compressor at less than peak pressure rise carries with it a reduction in operating efficiency and performance, there is a trade-off between stall margin and performance.

DISCLOSURE OF THE INVENTION

An object of the present invention is to control stall and surge in a compressor.

According to the present invention, the change in the level of circumferential flow asymmetry is detected along with the time rate of change of the inlet (annulus) average flow to control compressor bleed flow, thereby modulating total compressor flow.

According to the invention, a circumferential spatial pattern or other measure of asymmetry of the compressor flow is determined from a plurality of compressor inlet sensors, and the pattern is resolved into a first term representative of a level of asymmetry in the flow properties that is summed with a second term that represents the time rate of change in the average compressor flow.

According to one aspect of the invention the first term is proportional to the first spatial Fourier coefficient |SFC1|, indicative of the level of asymmetry of the circumferential gas flow properties.

According to another aspect of the invention, the first term is proportional to the square of the first spatial Fourier coefficient |SFC1|. The second term is proportional to the time rate of change of total compressor flow, determined, for example, from pressure sensors in the compressor flow path. The two signals are scaled and summed to produce a bleed control signal A_{con}, as expressed by $A_{con}=k_1\alpha+k_2\delta$, where A_{con} is the area, α is $|SFC1|^2$ and δ is the time rate of change of the annulus averaged mass flow.

According to one aspect of the invention, an integral term is added to the sum of the two terms which represents the temporal integral of the difference between the instantaneous level of asymmetry and a maximum desired level for the compressor.

According to another aspect of present invention, the magnitude of the integral term will range between two limiting values (min/max).

A feature, of a particular embodiment of the present invention, is the use of arrays of pressure sensors to sense the flow properties within the flow path, rather than making direct flow measurements. Direct flow measurement devices are generally less reliable than pressure measurement devices, and much more difficult to implement in a real world application. Pressure sensors are more easily incorporated into a control system that must operate in a harsh environment.

The stall and surge controller of the present invention has application to any compression (pumping) system that includes a compressor subject to the risk of rotating stall and/or surge. Examples include gas turbine engines and cooling systems, such as some air conditioning systems or refrigeration systems. The invention has application to a variety of types of compressors, including axial flow compressors, industrial fans, centrifugal compressors, centrifugal chillers, and blowers.

Another feature of the present invention, is that the bleed system responds to both the asymmetric flow properties and